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THE SHIP RESPONSE TACTICAL DECISION AID - PHASE I

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DTRC/SHD-1220-02 The Ship Response Tactical Decision Aid- Phase I

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19. were in better agreement with measured motions than did observed wave data. Motion predictions, based on observations were consistently less than the real time motion measurements. The mean difference between measured and predicted motion was generally less than ±20% for the buoy and the radar measured wave inputs.

A more sophisticated SRTDA is currently being developed in Phase II. This incorporates input of a directional spectrum of waves based on measurements by a ship's SPS-64 radar. A level of operability of the ship's system is displayed for a range of headings and speeds, given the sea conditions.

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ABSTRACT

The Ship Response Tactical Decision Aid (SRTDA) is a seakeeping tool that will provide Battle Group Commanders and Commanding Officers advisories on ship speeds and headings to optimize operations and minimize casualties during the conduct of evolutions which become hazardous in heavy seas. The SRTDA is under development in two phases under the Battle Group Environmental Enhancement Program. Phase I, is presently being transitioned to fleet use under the Tactical Environmental Support System Program (TESS). Contours of ship motion in the form of polar plots which display heave, pitch, and roll are displayed as a Phase I product with visual observations of sea conditions as program input.

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A more sophisticated SRTDA is currently being developed in Phase II. This incorporates input of a directional spectrum of waves based on measurements by a ship's SPS-64 radar. A level of operability of the ship's systems is displayed for a range of headings and speeds, given the sea conditions.

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INTRODUCTION

Throughout the ages, ships have had to operate in adverse conditions, including strong winds, precipitation, currents, sub- freezing temperatures and ocean waves. The most common and influential of these conditions is ocean waves. When sea conditions worsen, the operational capability of a ship decreases. This degradation can range from mild cases of motion sickness amongst crewmembers, to severe restrictions on equipment operability. In extreme cases, a ship's capability can be reduced to the point where survival becomes the primary task of the day.

Mission requirements may not always allow naval combatants and auxiliaries to avoid storms and extreme wave conditions. In support of the invasion of the Philippines in 1944, ships of the Third Fleet were caught in a typhoon, in the Western Pacific. Excessive environmental loading by rough seas resulted in the loss of three destroyers (Reference 1).

Heavy seas have other implications in addition to ship survivability. Of less severity, but nonetheless significant, a ship's ability to utilize weapons and sensor systems to perform necessary operations can be degraded from maximum operability in calm seas to total inoperability in heavy seas. A similar statement can be made with regards to manpower intensive evolutions such as underway replenishment (UNREP).

Traditionally, in rough weather situations, best possible ship speeds and headings have been determined from weather information, observations of the environment, a knowledge of the shiphandling, and seamanship. The results are generally satisfactory in mildly confused seas. When the seas become very confused, and with increasing sea state, it becomes difficult to determine the best possible course and speed. In addition, the need to conduct a variety of operations utilizing a diverse set of weapon and sensor systems create a situation where a "seat of the pants" estimate of course and speed is simply not sufficient. Ship motion limitations associated with one evolution or system may be in conflict with another. As a result, a particular course and speed may maximize efficiency of one system, yet severely limit efficiency of another. This can create a hazardous situation when combat capability or survivability of the ship is dependent on the effective use of both systems.

Battle Group commanders oversee the operations of many types of ships in the Battle Group. Since seakeeping characteristics vary with each hull form, a Battle Group Commander faces the task of maximizing the effectiveness of a group of ships which may significantly differ in the individual response to a given seaway. If the Commander could utilize a tool that would predict the performance of each of his ships to the immediate sea conditions and indicate which weapons and sensors on each ship would be effective, he could more effectively employ the assets of the Battle Group. Such a tool is currently being developed.

The Ship Response Tactical Decision Aid (SRTDA) is a computer program that will predict ship motion and its effect on ship systems and evolutions when given real time wave measurements. The ocean waves will be measured using the ship's surface

search radar. The wave data will then be inputed to the SRTDA which is loaded in the Navy standard shipboard HP-9020 computer. A guidance of ship capabilities, relative to the sea conditions, will then be available to the Commander to aid the assessment of mission effectiveness of the Battle Group.

This report will provide background information on the SRTDA; the approach, the methods and the equipment. The system was divided into two phases for development. Phase I, which is currently being transitioned into the fleet, will be reviewed along with results from a validation trial. Phase II will be discussed, including the progress and plans.

BACKGROUND

BATTLE GROUP PROGRAM

The Ship Response Tactical Decision Aid is one of a number of programs that is being developed under the Battle Group Environmental Enhancement Program. The Battle Group Program is utilizing applied oceanographic technology to enhance the operational capability of U.S. Navy Battle Groups. Improved definition of local atmospheric and oceanographic effects on ships' weapons and sensors will give Battle Group Commanders and individual ship Commanding Officers an immediate determination of a ship's constantly changing capability due to the environmental conditions.

The Ship Response Tactical Decision Aid will do more than simply determine whether or not various sensors and weapon systems are presently within motion limits for effective operation. The SRTDA will provide ship operators with guidance as to alternative headings and speeds which may be available to allow the sensor, weapon, or system to operate at an increased level of effectiveness. This guidance is also valuable for casualty avoidance during adverse weather conditions.

SRTDA DEVELOPMENT

The development of a SRTDA is based on the calculation of ship motions given near real time measurement of the sea conditions. In order to calculate ship motions, it is necessary to have on hand the Response Amplitude Operators (RAOs) of the desired ship and a description of the sea conditions. The RAOs can be calculated using motion prediction programs and they are unique to each hull form and loading condition. The sea conditions can be obtained from observations, forecast models, or measurements.

One of the more sophisticated ship motion computer programs is the U. S. Navy's standard Ship Motion Program (SMP)(References 2 and 3). An outgrowth of a previous ship motion computer program developed at the David Taylor Research Center (DTRC), SMP is the standard ship motion prediction tool used in the Navy's ship design process. Based on hull geometry and loading, RAOs are calculated for each ship class. The RAOs used in the Ship Response Tactical Decision Aid are used with all the general assumptions associated with SMP.

The ocean wave input comes in a variety of forms, depending on the resources available. The waves can be measured using a directional sensing wave buoy, a shipboard radar, or other sensor. The waves can be predicted using a model such as the Global Spectral Ocean Wave Model (GSOWM) operating at the Fleet Numerical Oceanography Center in Monterey, California. GSOWM is a refinement of the Spectral Ocean Wave Model (SOWM) (Reference 4). In the absence of wave measurements or GSOWM as technical input, the sea conditions can be observed, using significant wave height, modal wave period, and predominant wave direction as parameters for input to the program. Each of these forms of wave input will be discussed in a later section. In each case, the wave data must be spread into the format of a matrix of frequency and direction, similar to the format of the stored RAOs, so as to expedite calculations of ship motion.

Wave information measured by a wave buoy independent of the ship is considered to be in the fixed frequency domain, while the ship is interacting with the waves in the encountered frequency domain. When calculating a spectral ship response from buoy measured wave spectral energy and the ship RAOs, the wave spectrum must be converted to the encounter frequency. However, during general operation of the SRTDA, wave information will not be obtained from buoy sources but rather from visual observation or ship's radar measurements recorded in the encounter frequency domain. In addition, if only the root mean square (RMS) values are required, the ship response can be calculated in either frequency domain, as they are statistically equivalent (See Reference 2). The computed ship motion predictions from the SRTDA are currently limited to RMS values of heave, roll, and pitch. Thus for general use, the wave data will not have to be transformed in frequency to match the RAO data.

In the mid-1970s, a method of displaying predicted ship responses was developed. The responses were displayed in a speed polar plot form. The response could be one of a variety of statistical parameters, such as RMS or Single Significant Amplitude, (SSA) for a host of motions, e.g., heave, pitch, roll displacements, and accelerations at a point on the ship, to name a few. A separate page was generated for each condition, i.e., combination of statistical parameters and motion. This resulted in a catalog of ship responses to provide operator guidance for a given ship (Reference 5). The advent of the desktop computer not only provided rapid calculations in the field, but also provided a means of rapidly displaying the results. For each ship/sea condition a near real time speed polar plot could be displayed on the terminal screen (See Fig. 1). If a permanent record is required, a hard copy could then be provided. Operation of the SRTDA program has been detailed in Reference 6.

METHODS AND EQUIPMENT

As mentioned earlier, the development of the Ship Response Tactical Decision Aid consists of two phases. The essential differences are in the quality of the input wave data and the inclusion of system motion limits.

SEAWAY DESCRIPTION

Phase I of the SRTDA employs an observation of the significant wave height, the modal wave period and the primary wave direction as a basis for the input wave data. These wave parameters are then used to calculate a longcrested Bretschneider spectrum. A shortcrested spectrum is then calculated by applying a cosine squared spreading function of ± 90 degrees to the longcrested Bretschneider spectrum.

The wave input to the Phase II SRTDA is designed to be technically more sophisticated. Utilizing a directional wave spectrum, the representation of the seaway would be more detailed. Energy densities would be distributed by wave frequency and direction. The data would be collected using the ship's own surface search radar or the GSOWM spectra.

HARDWARE DESCRIPTION

The hardware of the Ship Response Tactical Decision Aid currently consists of the U. S. Navy's desktop HP 9020 computer, with ancillary storage devices; and will include the ship's surface search SPS-64 radar. The SPS-64 radar is the upgrade to the current SPS-10 surface search radar. The SPS-64 is being installed on new ships and is being backfitted on ships already in the fleet.

The use of a shipboard radar for measuring ocean waves has been of interest to a number of investigators in recent years (References 7, 8, 9). The general means of collecting the wave data has been photographing the Planned Position Indicator (PPI) for a series of radar sweeps. The photographs would be optically digitized, Fast Fourier Transformed, (FFT'd) and then spectral processing of the data performed. While this method produces a relative wave number spectrum, there is no measurement of the wave height. Any inclusion of spectral densities is by means of mathematical modeling. In addition, the process is time consuming, involving photographic services and optical digitizing equipment.

A method to circumvent the limitations of the photographic data collection procedure is to tap directly into the PPI and record the X and Y voltages using a computer. This method of radar wave data collection has been under development at the Naval Research Laboratory (NRL) by Trizna (References 9 and 10). The data collection is independent of the radar console and is transparent to the PPI display. It does not require mounting photographic equipment over the display, thus freeing the display for operational use. The measured wave data can be collected and analyzed with the computer in a matter of minutes, at which time it could be inputed to the SRTDA.

NRL's radar measurement of ocean waves was developed using the commercial Raytheon Pathfinder Marine Navigation radar. The MIL-SPEC version is the SPS-64 surface search radar. The SPS-10 radar, predecessor to the SPS-64, is not as suitable for wave measurement. The main differences between the SPS-64 and the SPS-10 are the signals used for generating the pointing direction of the PPI display, and the log

versus linear receiver design (Reference 10). The SPS-64 uses an analog sine and cosine signal while the SPS-10 uses a digital synchro signal. The SPS-64 radar uses a logarithmic amplifier in the final receiver driver, which covers the full 60-db dynamic range of the radar. Thus all signal levels which may be encountered are covered by one fixed setting, and this output is digitized by an 8-bit digitizer for analysis. The SPS-10 has a linear amplifier, with roughly a 20-db dynamic range, which is adjusted to cover the range of interest depending on sea state and sea clutter. Additional comments on the unsuitability of the SPS-10 will be further discussed in the Validation section.

The capability of a surface search radar to measure ocean waves is being developed. The SPS-10 wave measuring system, which was exercised during the full scale trials mentioned below, produces an image of a wave number spectrum (Fig. 2). The typical wave number spectrum displayed in Fig. 2 is a radial plot of wave number versus direction. The wave length values displayed along the abscissa of Fig. 2 represent a translation of wave number to wave length for purpose of convenience. The SPS-10 radar wave measuring system is capable of discerning the wave frequencies and the primary wave direction with a 180 degree ambiguity. (The final determination of wave direction is made with supplementary information.) This system is not capable of measuring the wave height. Testing of an early version of the radar system has been conducted at the U. S. Army Corps of Engineers Coastal Engineering Research Center's (CERC) offshore pier at Duck, North Carolina and aboard several ships at sea.

The SPS-64 radar wave measuring system will provide spectral parameters as a basis to calculate a directional wave spectrum. It will be capable of discerning the wave frequencies, the wave directions and the wave orbital velocities to yield wave height. In order to adequately sense the orbital velocities, a sample rate of 100 Megahertz (Mhz) must be employed. Initial testing of the SPS-64 has been conducted also at the CERC pier and at sea.

THE PHASE I SRTDA

The Phase I Ship Response Tactical Decision Aid was developed to provide an interim capability that would be available to the fleet while the more technically sophisticated Phase II SRTDA was being developed. A major difference is the quality of the input of the ocean wave conditions.

SYSTEM DESCRIPTION

The Phase I SRTDA was designed to employ visual observations to define the significant wave height, modal wave period and primary wave direction. Such observations are best when the seas are well defined, and unsatisfactory when seas become complex; thus the impetus for developing a shipboard wave sensor has been defined out of the need to provide accurate wave measurements.

The basic method of motions computation employed in the Ship Response Tactical Decision Aid is described by Meyers, et al (References 2 and 3). In this method the wave

conditions must be specified in terms of wave spectra. Since the definition of the seaway onboard ship is presently limited to visual observations, the primary wave parameters, i.e. wave height, period and direction of wind waves and swell, must be converted into wave spectra. To conform to this requirement the Bretschneider formulation is used to model the wave spectra from the given primary wave parameters.

In order to expedite the calculations aboard ship, most of the intermediate computations required for the final estimates of the RMS heave, pitch and roll motions are carried out in advance. The results of the intermediate computations for each ship class are stored in a separate file, known as a Precomputed Ship Response Matrix (PSRM). The nature of the computation described by Meyers, et al is such that most of the work in the prediction of RMS motions can be carried out for unit significant wave height; that is, before the significant wave height is specified. This fact is taken advantage of in the construction of the PSRM.

In particular, because pitch and heave are considered to be linear motions, the RMS pitch or heave predicted for a given ship speed, heading and wave spectrum is directly proportional to the significant wave height. Consequently, the intermediate data retained in the matrix for pitch and heave is in the form of RMS values for unit significant wave height.

Because viscous damping has a significant effect upon ship rolling, roll is considered to be a weakly nonlinear response. Accordingly, the prediction methods of Meyers, et al for RMS roll involve an iterative procedure. In this procedure, for each given ship speed and heading, eight provisional roll responses to regular waves of unit amplitude (RAOs) are calculated for eight assumptions of *actual* roll amplitude. (The roll amplitudes assumed range from 0.5 to 40 degrees.) Given a wave spectrum and the eight provisional RAO's, eight provisional RMS roll values are computed as if each provisional RAO defined a linear system. The final RMS roll estimate is made by interpolation between the eight provisional RMS values, such that the predicted significant roll amplitude (twice the RMS value) corresponds to the (interpolated) value of the initially assumed roll amplitude in regular waves. For purposes of the PSRM, the provisional RMS roll calculations are carried out for unit significant wave height and these are the data retained in the matrix.

In the construction of each PSRM, a family of ten Bretschneider wave point spectra is developed for the odd numbered modal wave periods between 3 and 21 seconds, each for a unit significant wave height. This family is ultimately used to represent swell of unit height. The family of longcrested spectra are "spread" using a cosine square function to produce shortcrested spectra. The resulting family of ten shortcrested spectra are used to represent wind waves of unit height. Each member of the two spectrum families is multiplied in turn by the pitch and heave RAOs, and by the eight provisional roll RAOs, to produce a form of ship response spectra, which are in turn integrated and the square root of the result gives the predicted RMS values for unit significant height. The procedure is carried out for all the pitch and heave RAOs and provisional roll RAOs

obtained for combinations of ship speeds of 0 to 25 knots, every 5 knots, and headings of 0 to 345, every 15 degrees. Since the calculations of motions on the centerline take advantage of ship symmetry, the relative headings of only one side of the ship are required. This yields a total of 13 headings including the 0 and 180 degree headings. The PSRM thus contains ten values of RMS motion per unit significant wave height (pitch, heave, and eight provisional values for roll) for each combination of shortcrested seas, longcrested seas, 10 wave periods, 6 speeds and 13 headings.

There is a PSRM for virtually every class of ship in a Battle Group, in addition to a few that are not actually Battle Group contingents. The current 56 ship classes and loading conditions that are represented by PSRMs are listed in Table 1. These PSRMs are stored on the HP 9020 hard disk for immediate access to any ship class of interest to the operator.

When the SRTDA program is run, significant wave heights, periods and directions of wind wave and swell are entered. For each speed and heading the program interpolates the ten values of RMS motion per unit significant wave height of wind generated waves between the appropriate results for assumed wind wave periods. The results are then scaled to the specified significant wave height. The final estimate of RMS roll is made by interpolation among the scaled provisional values. The entire procedure is carried out similarly for the specified swell conditions to yield estimates of RMS pitch, heave and roll for the specified wind wave and swell. The RMS motions due to the wind (shortcrested) seas and the swell (longcrested seas) are combined by a square root of sum of squares procedure to yield final estimates of RMS pitch, heave and roll, which are then multiplied by two for an estimate of total Significant Single Amplitude (SSA) motions response.

A speed polar plot is displayed on the computer screen detailing contours of roll, pitch or heave motions. The predicted SSA motion displayed is that which the ship can expect to encounter at the displayed ship speed and course. For example, in Fig. 1, for the sea conditions listed the ship can expect greater than 9 degrees of roll at a course of 000 degrees true and a speed of 15 knots. If a roll motion sensitive operation is required, then a change of ship course to 328 degrees would reduce roll to 3 degrees, an acceptable level. Other examples of operator guidance are demonstrated in Reference 11. Note that the display is aligned with True North or Magnetic North depending on whether true or magnetic wave direction is input to the program.

VALIDATION METHODS

Computer models can be developed and used for a host of reasons, but to confidently use the models they must be validated for a range of typical conditions. The validation of the SRTDA would require a series of full scale trials covering a variety of ship types and a range of sea conditions. The problems associated with this attempt are twofold. First, the availability of ships on which to conduct the trials is limited. While every ship class is potentially available, not every available ship meets the radar

requirements and can provide the necessary testing time in its schedule. The SPS-64 radar is currently being back-fitted on combatants, but not many installations have been completed. Second, since it is not possible to control the sea conditions during a scheduled sea trial, it is difficult to test in a sufficiently large range of sea conditions to achieve adequate validation. However, it is possible to increase the probability of getting the desired seas by going to sea in the appropriate season in favorable locations as defined by wave climatological data.

Full scale validation of the Ship Response Tactical Decision Aid is underway, using two approaches. Installation of the software on ships of opportunity to be operated and evaluated by ship's crew is one approach. The other approach is to conduct full scale trials in which full scale motions are recorded as are environmental data for motion predictions.

In the first approach, the Phase I SRTDA is loaded on a shipboard computer. The Meteorological Officer, or other designate, would observe the environmental conditions (sea and swell) and enter the data into the model to predict ship motions. During the period of the recorded sea conditions, the experienced pitch and roll motions could be recorded from the ship's gyroscope. The predicted and experienced ship motions would be collected for subsequent analysis and comparison.

It should be noted that the ship's inclinometer should not be used for measurement of roll and pitch. Inclinometers can indicate roll motion to be 1.5 to 2 times greater than true roll motion measured using ship gyros. (See Reference 12.)

The second approach is to conduct full scale trials accurately quantifying the sea conditions and ship motions for analysis. Such a full scale trial was conducted in April 1988 to validate the Phase I Ship Response Tactical Decision Aid. The ship, USS CONYNGHAM (DDG-17), was equipped with the SPS-10 surface search radar. Availability of the ship during the early spring provided an opportunity to encounter sea conditions that induced motions to the ship.

Description of Conyngham Trial

The trial plan called for defining the sea conditions while measuring ship motions at predetermined headings relative to the predominant wave direction. The waves were measured using an Endeco Type 956 directional wave sensing buoy and using the ship's SPS-10 surface search radar. Ship motions were measured using the ship's gyros and an independent accelerometer package. The ship's gyro repeaters were tapped to record roll and pitch motion. A DTRC accelerometer package was used to measure ship's vertical acceleration from which displacement was calculated. The package was located 7.0 feet (2.1 m) on the port side of the centerline, 205.0 feet (62.5 m) aft of the forward perpendicular, and 2.3 feet (0.7 m) above the 13.0 foot (4.0m) waterline reference. Roll and pitch are considered constant at any location on the ship and heave is defined as the vertical displacement at the center of gravity (CG). The CG of the CONYNGHAM is located 18.7 feet (5.7 m) above the keel, therefore, the vertical acceleration measurement

is 3.3 feet (1.0 m) below CG and 7.0 feet (2.1 m) left of the centerline. The longitudinal location of CG is 215.9 feet (65.8 m) aft of the forward perpendicular. This location is approximately 10.9 feet (3.3 m) aft of the accelerometer package. Since the distance between the location of CG and the location of the package is small, the difference in the vertical displacement at this location and a vertical displacement at the CG is considered to be negligible.

Four tests were conducted during the at-sea period. Each test began with a measurement of the sea conditions. The buoy was deployed and telemetered directional wave data to a receiver on board ship for 30 to 40 minutes, depending on the test. At the same time, the SPS-10 was collecting a series of two minute samples of the wave field within a one kilometer radius about the ship. Visual observations of the waves were also recorded during this time. At the end of the buoy data collection, the buoy was retrieved and the ship proceeded to run five legs of an octagonal trial course pattern oriented to the predominant wave direction. The first leg was head seas (0 degrees relative), then bow seas (45 degrees relative), then beam seas (90 degrees relative), then quartering seas (135 degrees relative), and finally following seas (180 degrees relative). Each leg of the octagon was run for 20 minutes at a nominal speed of 10 knots.

In reality, the actual relative headings were different than the desired relative headings. The initial heading selected for each test octagon pattern was based on the visual observation. Since the observations did not agree completely with the buoy and radar measured predominant wave directions, the headings did not follow the ideal case described above. The initial heading chosen for octagon patterns one and three turned out to be bow seas with the predominant wave direction off the starboard bow. These two octagons thus were conducted for bow seas, then head seas, then bow seas (opposite to the first bow seas condition), then beam seas, and then quartering seas but not following seas. Octagon four did not include head seas as the ship's schedule limited further testing time. Octagon two was completed for head, bow, beam, quartering and following seas. The legs of each octagon were separated by 45 degrees, but did not line up with the desired 0, 45, 90, 135, and 180 degree relative headings. Therefore, the headings were delineated as follows: head seas, ± 22.5 degrees; bow seas, 22.6 - 67.5 degrees; beam seas, 67.6 - 112.5 degrees; quartering seas, 112.6 - 157.5 degrees; and following seas, 157.6 - 202.5 degrees.

The mean speed for each leg remained constant but between legs varied from 10.4 to 12.3 knots, with an exception of one leg conducted at 19.7 knots. The input of the ship speed and heading into the Phase I SRTDA for the predicted motions were each selected to agree exactly with the measured ship speed and heading relative to the predominant wave direction.

Since the dynamic range of the SPS-10 radar linear amplifier was limited to 20-db, adjustments to the PPI display for intensity and clutter were required to optimize each wave measurement to cover the wave energies of interest. These adjustments were acceptable, albeit cumbersome during the sea trial during time periods when the

radar was dedicated exclusively to wave measurements. While tracking surface contacts, shipboard watch standers must adjust the PPI intensity to minimize clutter and enhance the display of other ships. Radar wave measurements, however, need to observe the clutter as a source of wave data. As a result, it is impossible to simultaneously conduct wave measurements and track other ships on the SPS-10. Ship control of the radar thus impacted the effort to measure waves using the SPS-10 while running the octagon patterns.

Results

Comparisons are presented among the three methods of recording waves, i.e. radar, buoy, and observations. Comparisons also are made between calculated and measured ship motions.

A comparison of shipboard wave measurements is presented in Table 2. At first glance, one will note that visual wave observations tended to be broken down to a sea and swell component. This was done to conform with the standard format of Navy weather observation logs. Visual observations of wave height were made in feet due to preference of the observer. The visual observation in octagon three contained no seas component because only swell was observed to be present. Buoy measurements were placed in the sea or swell column of Table 2 based on the spectral bandwidth. Narrow banded spectra were entered in the swell column. Agreement of the observed waves and the measured waves varied. Variation ranged from close agreement to more than six seconds in period, 80 degrees in direction, and 3.0 feet (0.92 meters) in wave height. The larger differences of wave height is more the exception than the rule. The differences in the observed and measured periods and directions may have been caused by the speed and heading of the ship relative to the waves during the visual observation. Typically, wave height is easier to observe than is period or direction.

As indicated in Table 2, the significant wave height used with the radar input is the value measured by the buoy. This procedure was followed because the radar was not capable of measuring wave height. The comparison in significant wave height is between the buoy and observation. However, comparison is made of the period and direction, for all three types of wave measurement.

When making comparisons between the radar and the wave buoy measurements, one must consider the origins of the data. The radar spectra is based on a radar image which covers several square kilometers in only two seconds (Reference 10). In contrast, the buoy spectra was collected at a fixed point over a period of 30 to 40 minutes. The radar uses spatial averaging over a short period of time. The buoy utilizes temporal averaging at a fixed point over a long time.

Wave modal periods between the radar and the wave buoy were in good agreement. Wave direction values between the radar and the wave buoy were within 9 degrees with the exception of octagon four. This discrepancy might be accounted for in the buoy measurement. The assumption present in buoy analysis is that a single primary wave

direction is being sensed, with some finite azimuthal spreading, i.e., a mean angle and its first component. If more than one azimuthal component is present, then the pitch and roll analysis of the buoy forces a single spectral component to fit the buoy response with a mean direction between them (Reference 9). As a result, if similar spectral peaks are present, but in different directions, the buoy may average the direction. This problem is not present in the radar spectra displays.

Using the input of significant wave height, modal wave period, and predominant wave direction, the SRTDA program can represent Bretschneider shortcrested seas, i.e., waves spread ± 90 degrees about the mean direction, and longcrested seas, i.e., swell with no spreading. If the input of seas with a spreading of less than ± 90 degrees is desired, the sea conditions cannot be properly modeled. The input of seas must then be approximated to the closer of the two spreading conditions. For example, if a sea appears to be almost longcrested, a swell may better approximate the sea condition than would wind waves. Otherwise, the energy would be spread across ± 90 degrees. Therefore, when approximating with wind waves or a swell, the Phase I SRTDA will tend to incorrectly predict the motions to some degree, depending on the sea condition selected and the relative direction of the seas and ship.

Comparisons between measured and predicted ship motions made aboard USS CONYNGHAM are presented in Figs. 3 - 20. Wave inputs for the SRTDA predictions are displayed in Table 2. In the first set of figures (3 - 11), the results are grouped by octagon; five legs for each of octagons one through three, and four legs for octagon four. Again, there is one wave measurement for each octagon. In the second set of figures (12 - 20), the results are grouped by relative heading to the predominant seas. Each set of figures are divided into motion - heave, pitch and roll, and type of wave input - buoy, radar and observation. The results are plotted so as to directly compare the SRTDA prediction and the measured motion. The prediction is plotted against the ordinate and the measurement is plotted against the abscissa. If the prediction equals the measurement, the symbol defined in the legend will lie on the solid diagonal line. If the prediction is greater than the measurement, the symbol will lie above the solid diagonal line. And if the prediction is less than the measurement, the symbol will lie below the solid diagonal line. The dashed lines on either side of the solid diagonal line represents a predicted value 20% greater or less than the measured value.

Discussion

In order to determine a degree of accuracy of the predicted motions relative to the measured motions, the Phase I SRTDA motion predictions were examined at the following levels: predicted motion within ±20% of the measured motion; predicted motion between ±20% and ±40% of the measured motion; and predicted motion greater than ±40% of the measured motion. These results are listed in Tables 3 - 6.

One of the first apparent observations is the poor showing of predictions calculated based on the observed wave inputs, as shown in Table 3. Combining the heave, pitch and

roll predictions yields a mere 14% of the predictions to be within 20% of the measured motion levels. Sixty-three percent of the predictions were greater than ±40% of the measured motion levels. Looking at Table 4, it can be seen that octagons one and four have particularly poor comparisons for observations. This can also be seen in Figs. 5, 8, and 11, where these symbols are bunched up and well below the −20% line.

This poor showing may be more of an indication of the inadequate observation of the seaway by an experienced observer than a direct reflection on the Ship Response Tactical Decision Aid. However, it should be noted that the Phase I SRTDA utilizes the observed wave input and so it is important that observed data be obtained with a degree of accuracy for input to the program. Input of incorrect sea data could lead to incorrect predictions of ship motions resulting in poor quality speed and course selections.

As can be seen in Table 3, the results from the buoy input and the radar input are similar to each other, as would be expected. Almost half of the predicted motion levels lie within 20% of the measured motion levels. In the case of the buoy measured wave input, 75% of the predicted motions are within 40% of the measured motion levels. Likewise, 68% of predicted motion levels, based on the radar measured wave input, agree within 40% of the measured motion levels. Heave and pitch are generally predicted better than is roll, when using the buoy or radar measured wave input. This can be seen in Table 3, as well as Figs. 3 - 11.

The results shown in Table 3 have been rearranged in Table 5 to indicate the relative capability of the SRTDA to predict heave, pitch and roll. Heave and pitch are generally predicted better than is roll. Two thirds of the predicted heave and pitch motions lie within 40% of the measured motions, while only about half the roll predictions agree within 40% of the measured motion values.

An indication of the capability of the computer model itself to adequately predict ship motions can be considered by looking in Table 5 at the motions predicted from the buoy and radar inputs, ignoring the observation inputs for now. Roughly half of the heave and pitch predictions are within 20% of the measurements. The best agreement is for the calculation of pitch using the radar data as input. Sixty- three percent of the predicted levels are within 20% of the measured levels. Approximately three quarters of the heave and pitch predictions are within 40% of the measured motion levels, with a noticeable best of 89% for the calculation of heave using the buoy data. Approximately 40% of the roll motions predicted using the buoy and radar data are found within 20% of the measured roll motions. This information can be seen in a different perspective in Figs. 3 - 11.

The results presented with respect to relative headings of the ship and seas are displayed in Table 6 and Figs. 12 - 20. Once again, the results produced by the SRTDA are strongly influenced by the sea conditions. It can be seen that the buoy and radar measured wave inputs provide a better agreement with measured motions than does the wave observation input. The buoy and radar results indicate that the head sea, bow sea and beam sea conditions tend to be predicted better than the quartering and

following sea conditions. The number of samples for head and particularly following seas is low and so are statistically less significant than the other headings. Bow seas is the greatest occurring condition and indicates the greatest agreement of predicted and measured motions using the buoy and radar wave data as input. However, the bow sea condition using observed wave data as input is the worst of all the conditions and data inputs.

An overall statistical summary for each of the motions is shown in Table 7. The percent differences between the predicted and the measured motions are displayed. The mean and standard deviation of the differences have been calculated for which the buoy, radar and observed wave inputs each are used to calculate the predicted motion.

The mean values indicate that roll is underpredicted. Pitch is overpredicted, except for the observed wave input, and heave is generally non-biased, except for the observed wave input. In all cases, the observed input causes the predictions to be underpredicted. The scatter, as indicated by the standard deviation, is generally the least for the buoy input. Based on the mean and standard deviation of the differences between predicted and measured motions, the radar measured wave input yields the best results with the possible exception of the buoy measured wave input for prediction of roll motion.

In each of the methods of presenting the results, one thing is evident. In this full scale validation, the measurement of the sea conditions provides a better prediction of the ship motions than does the observation of the sea conditions. This comparison does not attempt, however, to look at the relative qualifications of wave observers.

Ideally, all the symbols in Figs. 3 - 20 would line up on the solid diagonal line, indicating exact agreement of the predictions with the measurements. This is obviously not the case. The results of some octagons are better than others, as seen in Figs. 3 - 11. The results of octagon one are bunched together for heave and pitch, but not nearly so for roll. This may result from the existence of a more complex sea condition than was inputed to the model. The results of octagon four, which were conducted in seas of almost twice the significant wave height of octagon one, are not as bunched as octagon one. Octagons two and three, which were conducted at almost twice the significant wave height of octagon four, have results that are spread over much of the displayed range of a given motion. This is expected for nearly longcrested, slightly spread seas, or even two distinct wave trains separated by a relatively small angle. As ship heading changes relative to the waves, its motion varies considerably.

On a general note, the following observations can be made of the results. (1) Roll is underpredicted for all three types of wave inputs, i.e., buoy and radar measurement, and visual observations. (2) The observation wave input generally contributed to an under prediction with a large amount of scatter. (3) The radar and buoy measured wave inputs provide a prediction of generally good agreement with the measurements.

Error Considerations

The approach used to determine the validity, or confidence, of the Phase I SRTDA is based on comparing predicted ship motions to actual measurements of the ship motions. In Figs. 3 - 20 are presented comparisons of individual runs, or octagon legs, in various forms. In Tables 3 - 6 are presented comparisons of groups of runs in various forms. Table 7 presents comparisons of predicted versus measured motions for each type of measurement for all headings and sea conditions. In each case, the motion predicted by the SRTDA is presented as a percentage greater than or less than the measured motion. The confidence in the predicted motions, therefore, is based on the confidence of the measured motions.

The uncertainty of the measured motions is based on a combination of accuracy and resolution of the instrumentation, resolution of the analog to digital converter, and sampling variability. Roll and pitch were measured using the ship's gyrocompass. A typical gyro such as the Sperry Mark 29 has an accuracy of 0.029 degrees. Vertical acceleration was measured using a Systron Donner ± 3 g accelerometer from which vertical displacement at the CG (heave) was obtained. The accelerometer has an accuracy of $\pm 0.1\%$ full scale.

The A/D converter is a 12 bit digitizer providing a resolution of 0.048%. For roll and pitch this translates to a resolution of 0.088 degrees. The A/D converter resolution of the accelerometer data translates to 0.0015 g.

The sampling variability of the time series data is much greater than the accuracy/resolution of the instrumentation. This is an inherent consequence of sampling time series data. The uncertainty of the SSA measured motions is presented in the form of 90% confidence limits. The number of degrees of freedom were calculated for each leg for the SSA motions of heave, pitch, and roll. A mean number of degrees of freedom were then calculated for each motion from which the lower and upper confidence limits were calculated. At a confidence limit of 90%, the mean uncertainty levels for heave were $+11.4\%$, -9.1%. The mean uncertainty levels for pitch were $+10.1\%$, -8.3%. And the mean uncertainty levels for roll were $+14.2\%$, -10.9%.

The sampling variability is about two orders of magnitude larger than the instrument error. Therefore, the instrument error is considered negligible. The uncertainty, at the 90% confidence level, of the measured motions will be the dominant source of an error. The levels of uncertainty on the order of $\pm 10\%$ are good considering the limited amount of testing time obtainable aboard U.S. Navy combatants. In order to reduce the uncertainty to about $\pm 5\%$, each leg of an octagon would have to be increased from 20 minutes to more than an hour. This is clearly an unrealistic request of a tightly scheduled combatant. Considering the measured motion uncertainty of approximately $\pm 10\%$, the predicted motion differences of $\pm 20\%$ are not unreasonable.

THE PHASE II SRTDA

The Phase II Ship Response Tactical Decision Aid is currently under development and will supersede Phase I. Two primary developments will improve the capability of the SRTDA. A significant improvement in the accuracy of the motion predictions will result from a more detailed definition of the sea conditions using the shipboard radar. Also, limits of operability resulting from wave induced ship motions will provide the Battle Group Commander a near real time capability of optimizing the Battle Group's course and speed to safely and effectively conduct operations. Software and graphic upgrades will provide a means of better interpreting the information.

Since a directional wave spectrum based on wave measurements will be available as input to the program, the calculation of the SSA motion will be at a more fundamental level than the method of using PSRMs. No longer will a Bretscheider wave spectrum be applied to RAOs from which ship motions are precalculated and stored. The variety of possible wave spectra are endless making futile the attempt to precalculate and store all possible ship motions. The basic calculation of the ship response, i.e., combining the wave energy with the RAO, will be performed in real time.

This has two consequences. The data file for each ship will be larger than the PSRMs, occupying more disk storage space. The PSRMs contained consolidated RMS motion information, while the Phase II data file will be the general RAO file that is normally developed for each ship (see Reference 2). Also, the execution time will increase, as calculations will be performed for each motion at every wave frequency, ship speed and heading. This is a more involved process than selecting the appropriate RMS motion from the PSRM file and scaling to the significant wave height and SSA statistic.

The capability to measure wave height, in addition to the wave frequencies and directions using the SPS-64 radar, is currently in the testing stage. Ultimately, the wave energy, frequency and directional information is intended to be integrated into a directional wave spectrum. The SPS-64 will continue to be tested at the CERC pier and at sea, including validation trials of the SRTDA.

A sea trial is planned to test the wave measurement capabilities of the SPS-64 radar. Simultaneous wave measurements will be made with the SPS-64 radar and a directional wave buoy. Ship motions will also be measured while the ship moves at a variety of headings and speeds. Directional spectra will be developed from the wave data and inputed to the Phase II Ship Response program. These predicted motions will then be compared to the measured motions. It is expected that the higher quality definition of the seaway will yield motion predictions which are in better agreement with the measured motions than the Phase I seaway definition.

Limits of operability will become effective by incorporating motion criteria into the SRTDA. Validated criteria for the various weapon and sensor systems used and operations conducted must be developed to provide respectable advisories of ship speeds and headings. Validated motion criteria can only be developed at sea while performing

the particular operations in conditions that will limit the operation. Many operations are likely to be ship class dependent. The many necessary operations conducted on ships and the large variety of ships lead to many sea trials. If the sea conditions during the testing period do not produce motions that limit operations, or conditions are too severe such that operations cannot be conducted, the limits cannot be defined. This possibly increases the number of trials needed to develop a comprehensive set of validated motion criteria.

The use of a motion criterion is demonstrated in Fig. 21 to display levels of operability for UNREP. This plot is similar to that in Fig. 1, but now in addition to two SSA motions levels plotted, three areas of operability are distinguished. The large clear area is the safe operating area. The single line hatching indicates that operations conducted at ship speeds and heading in this area of the plot should be conducted with caution. Finally, the cross hatching indicates that conducting operations at these speeds and headings will be hazardous. Though the limiting criteria used has not been validated (there are very few validated criteria existing), this information can be used during trials, as a reference point to help determine a valid limiting criterion. The motion demonstrated was roll. Other ship motions such as pitch and heave may also be limiting factors for a given operation.

In Phase I, a separate plot must be produced to display the motion levels predicted for each type of motion. In Phase II, motion criteria and areas of operability provide the mechanism of combining the three motions into a single plot. An area of operability is calculated for each motion, then are overlaid to provide one plot of operability based on heave, pitch and roll. The accuracy of the operabilities, of course, is pending development of validated motion limits.

CONCLUSIONS

The Ship Response Tactical Decision Aid is a seakeeping tool that will provide to Battle Group Commanders and Commanding Officers advisories on ship speeds and headings to optimize operations and minimize casualties. It is being developed under the Battle Group Environmental Enhancement Program in two phases. Phase I, which currently is being transitioned to the fleet via the Tactical Environmental Support System Program, provides contours of ship motion of heave, pitch, and roll. The wave input to the SRTDA relies on visual observations, which often does not accurately depict the ocean wave forcing function acting on the ship.

Phase II is currently being developed. It will incorporate input of a directional spectrum of the waves calculated from spectral components measured by the ship's SPS-64 surface search radar. A level of operability of the ship's systems or operations conducted will be displayed for a range of ship speeds and headings, based on the sea conditions. Three levels of operability will be indicated: safe, caution, and hazardous.

One validation trial has been performed to date for the Phase I SRTDA. Ship motions were measured against which predicted motions were compared. Predicted mo-

tions were heave, pitch, and roll based on visual observations, buoy measurements, and radar measurements of the sea conditions. Input of wave information was limited to significant wave height, modal wave period, and predominant wave direction to accommodate the Phase I program. The SPS-10 radar that was used did not have the capability to provide wave height, so the buoy measured wave height was used in the radar wave input.

Buoy and radar measured wave inputs to the SRTDA consistently provided motion predictions that were in better agreement with the measured motions than did observed wave inputs. The motion predictions, based on the observed wave input were consistently underpredicted. Roll was underpredicted using the three types of wave input. Radar data provided motion predictions with the least bias from motion measurements. Scatter was generally lowest for buoy generated predictions versus measurements. Overall, the mean difference between measured and predicted motions was generally less than $\pm 20\%$ for the buoy and radar measured wave inputs.

The Phase I SRTDA is not the absolute tool for predicting ship motions given an input of sea conditions. At this stage, the SRTDA is most valuable as an advisory of the best course and speed in which to operate relative to other courses and speeds. However, the outlook is very promising towards a more accurate and reliable means of predicting ship motions. The weak link in the system is a realistic input of the sea conditions. This is being addressed in the form of using a shipboard SPS-64 radar to measure the waves. Using the SPS-64 radar will provide a tremendous improvement in the description of the waves over that of visual observations. Its development is continuing and is now in the testing stage.

Validated motion limits for the various operations conducted on ships must be developed. This process will take time, as many motion induced limits are still not validated. A steady effort to determine these limits, starting with the most critical and sensitive, is recommended. Once these limits are validated, then the U.S. Navy will be armed with a Ship Response Tactical Decision Aid, optimizing Battle Group and ship operability, effectiveness and safety in the ever potentially hostile ocean environment.

ACKNOWLEDGEMENTS

The kind cooperation of the USS CONYNGHAM, under the capable leadership of Commander David Rose, allowed the ship motion and wave measurements to be carried out. The efforts of Dr. Dennis Trizna of the Navy Research Laboratory (NRL) were essential in providing the radar data utilized in this study. Special thanks is extended to Mr. John Dalzell of DTRC for his efforts and guidance.

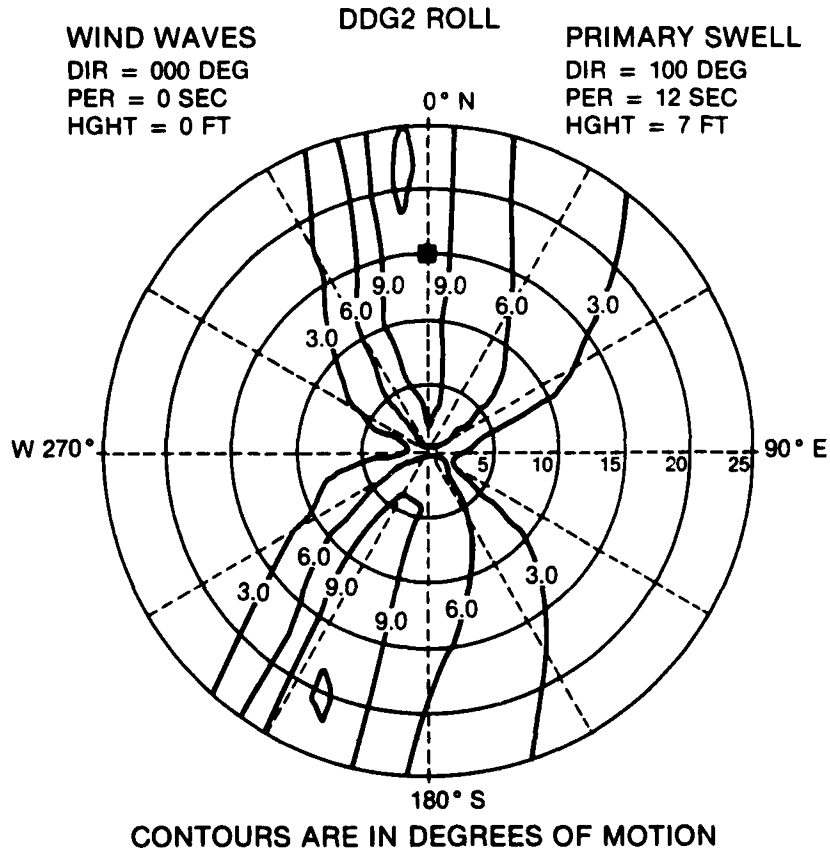
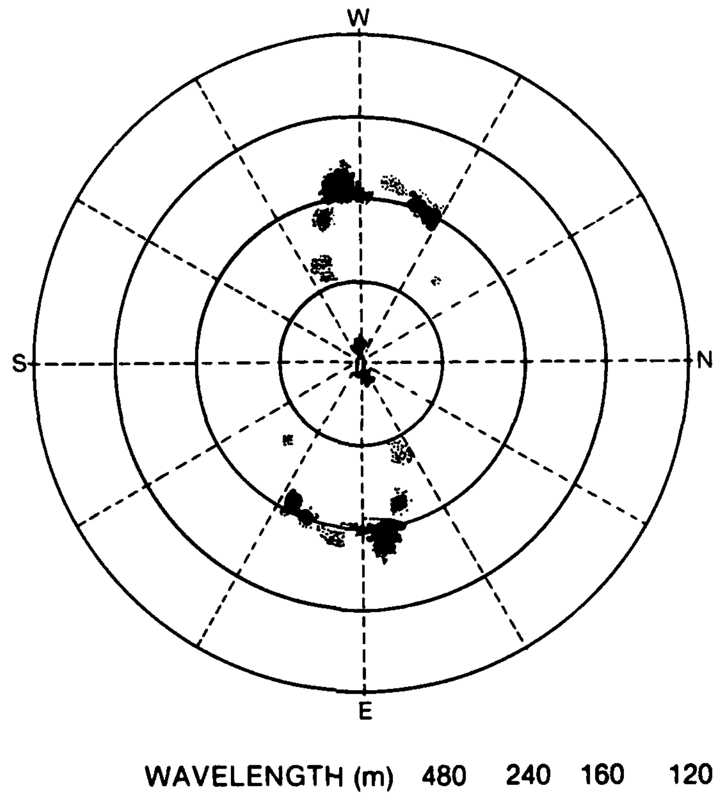


Figure 1. Speed Polar Plot of SSA Roll Motion.



NOTE: Radial scale is measured wave number.

Figure 2. Wave Number Spectrum Produced from Waves Measured by SPS-10 Radar (After Trizna, Ref 9.)

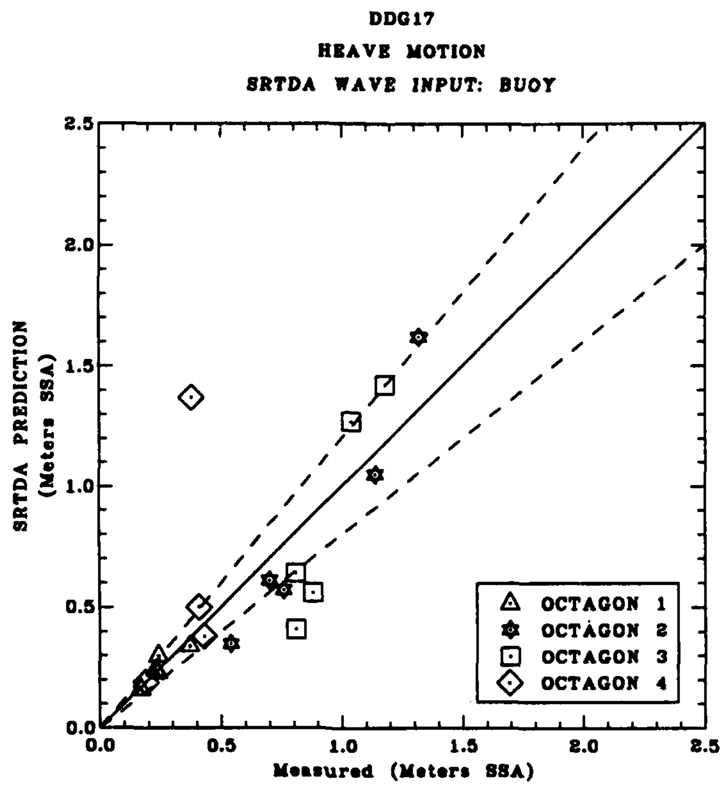


Figure 3. Predicted vs. Measured Heave Motions Grouped by Octagons. Predicted Motions Based on Buoy Measured Waves.

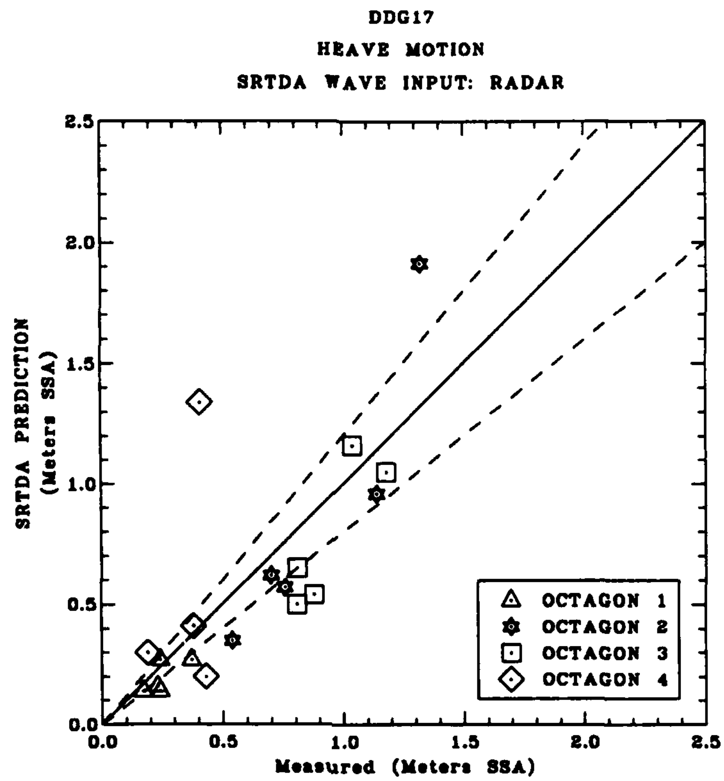


Figure 4. Predicted vs. Measured Heave Motions Grouped by Octagons. Predicted Motions Based on Radar Measured Waves.

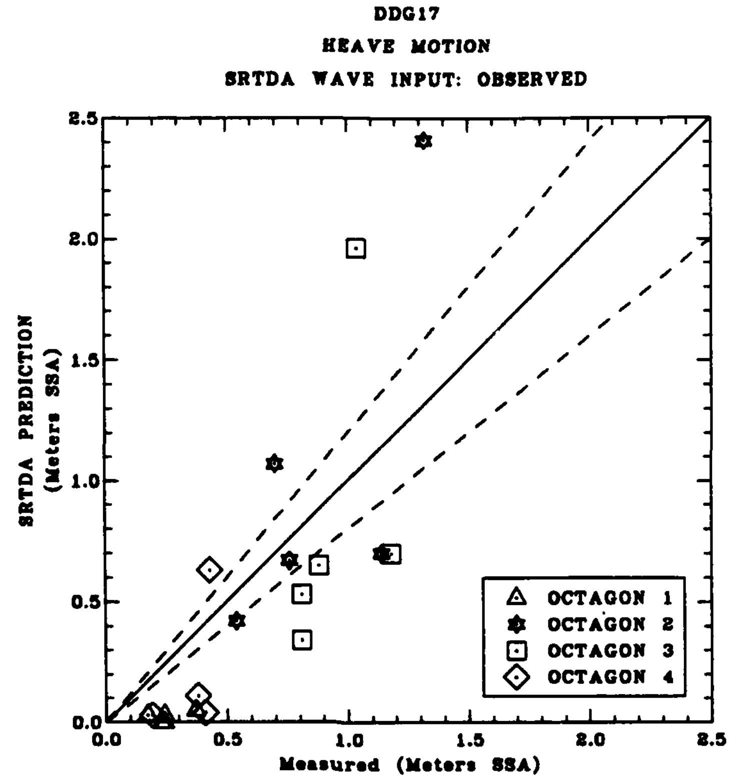


Figure 5. Predicted vs. Measured Heave Motions Grouped by Octagons. Predicted Motions Based on Observed Waves.

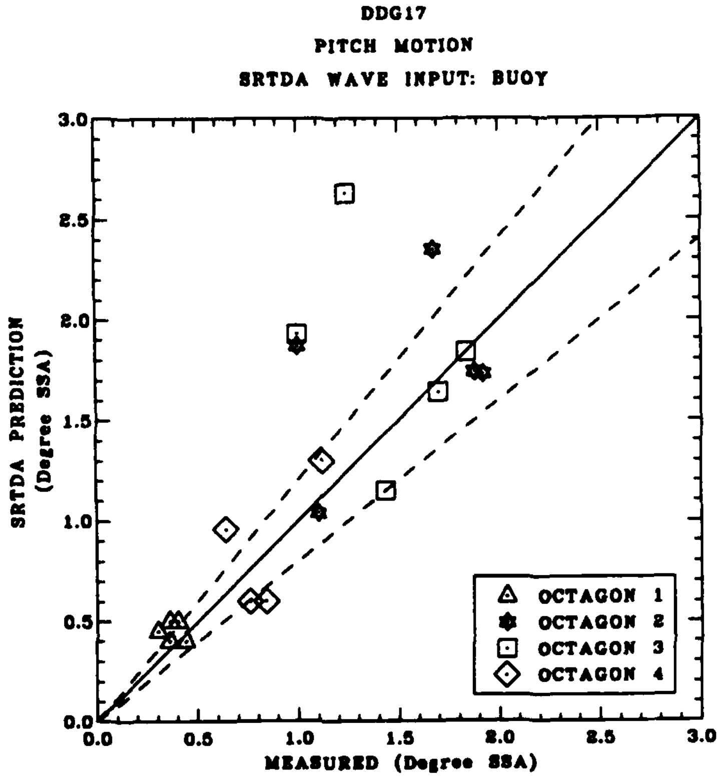


Figure 6. Predicted vs. Measured Pitch Motions Grouped by Octagons. Predicted Motions Based on Buoy Measured Waves.

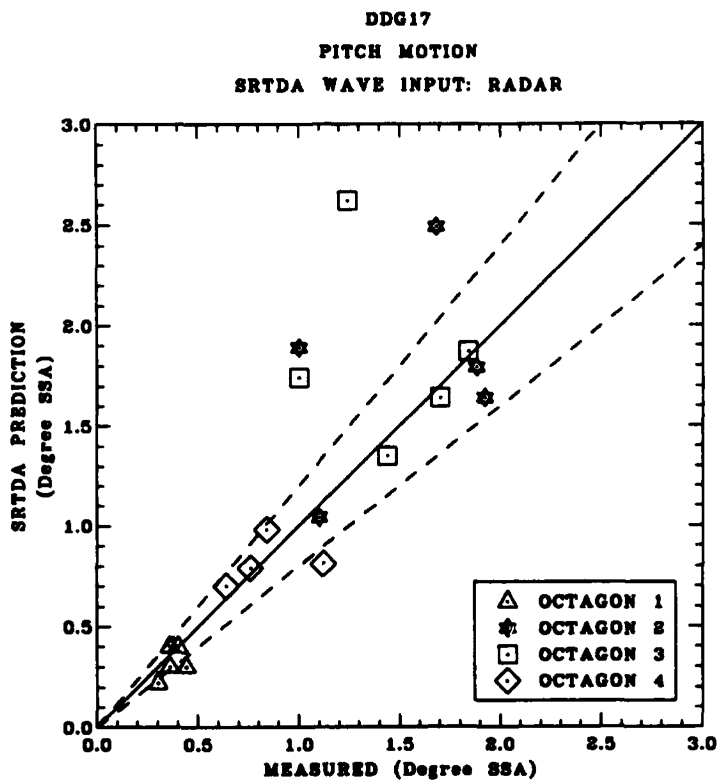


Figure 7. Predicted vs. Measured Pitch Motions Grouped by Octagons. Predicted Motions Based on Radar Measured Waves.

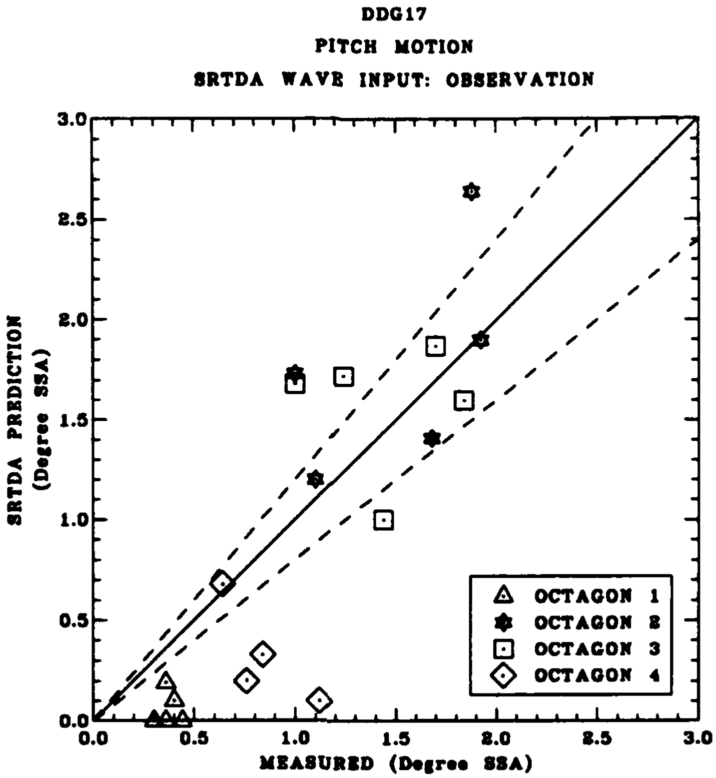


Figure 8. Predicted vs. Measured Pitch Motions Grouped by Octagons. Predicted Motions Based on Observed Waves.

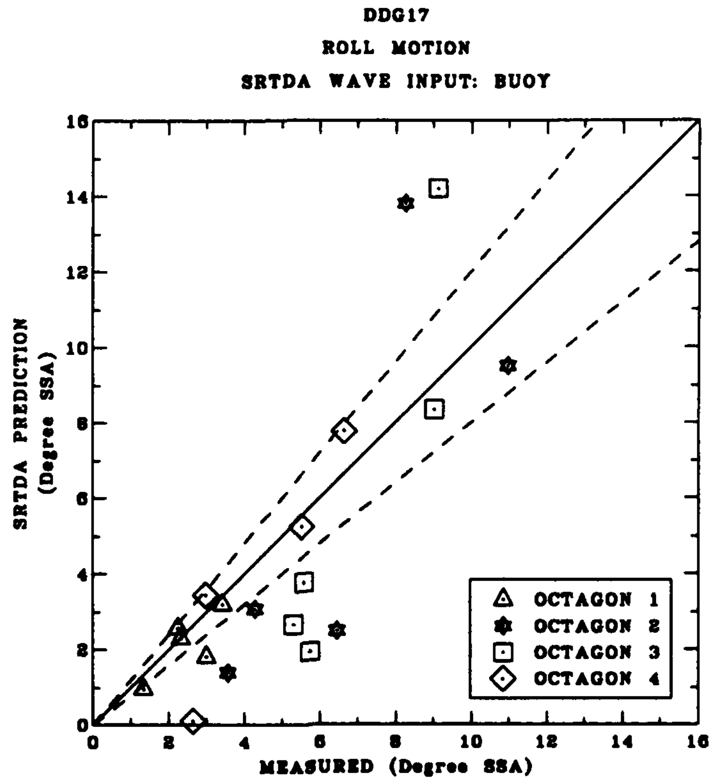


Figure 9. Predicted vs. Measured Roll Motions Grouped by Octagons. Predicted Motions Based on Buoy Measured Waves.

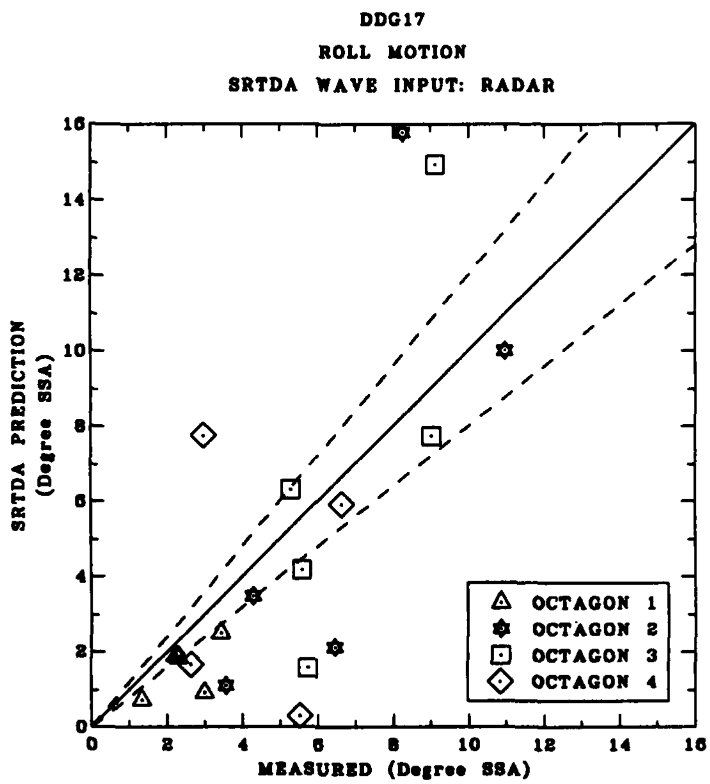


Figure 10. Predicted vs. Measured Roll Motions Grouped by Octagons. Predicted Motions Based on Radar Measured Waves.

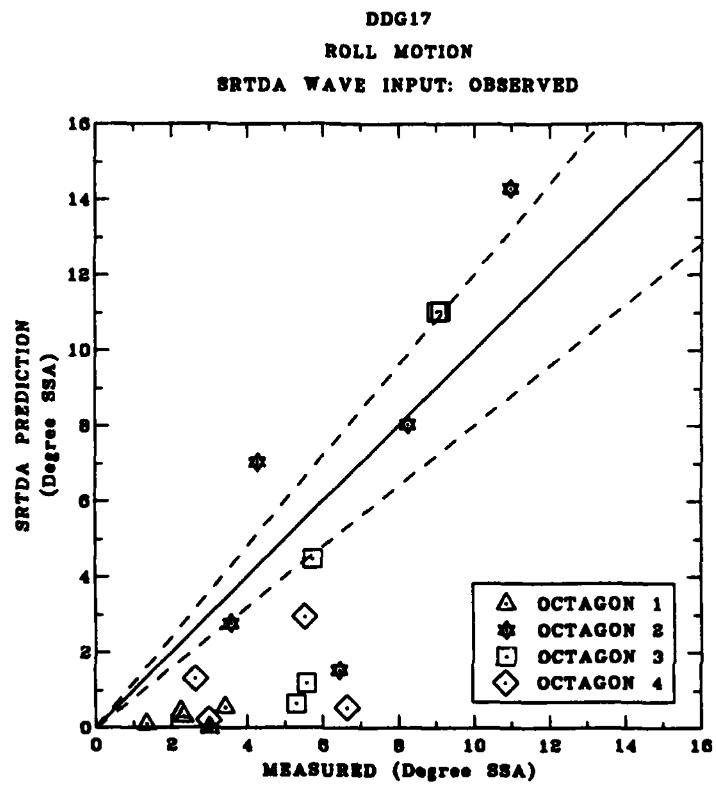


Figure 11. Predicted vs. Measured Roll Motions Grouped by Octagons. Predicted Motions Based on Observed Measured Waves.

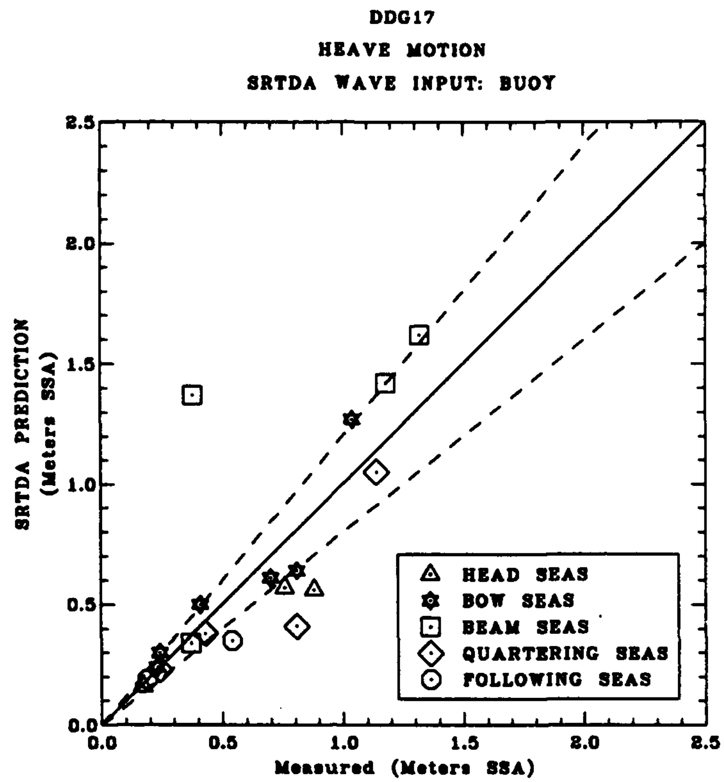


Figure 12. Predicted vs. Measured Heave Motions Grouped by Heading. Predicted Motions Based on Buoy Measured Waves.

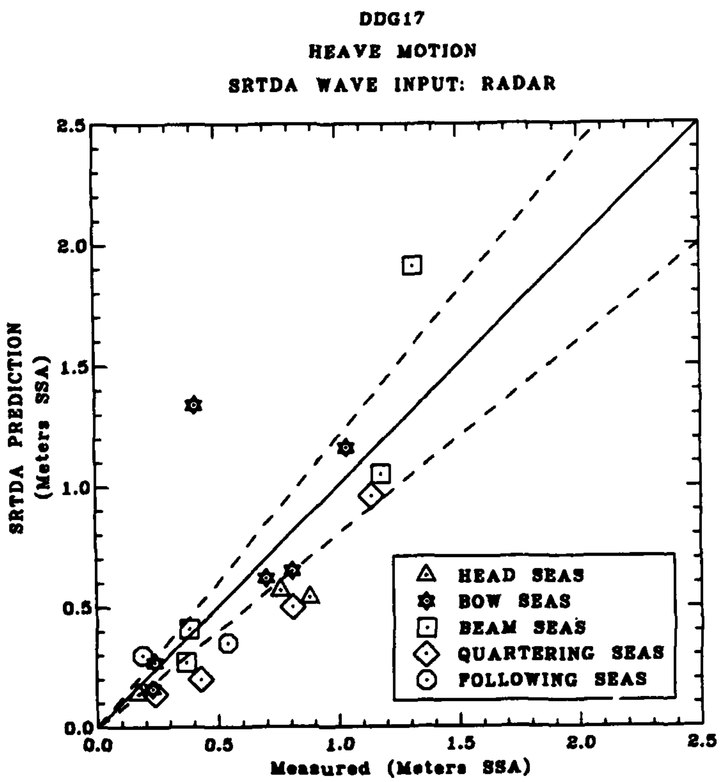


Figure 13. Predicted vs. Measured Heave Motions Grouped by Heading. Predicted Motions Based on Radar Measured Waves.

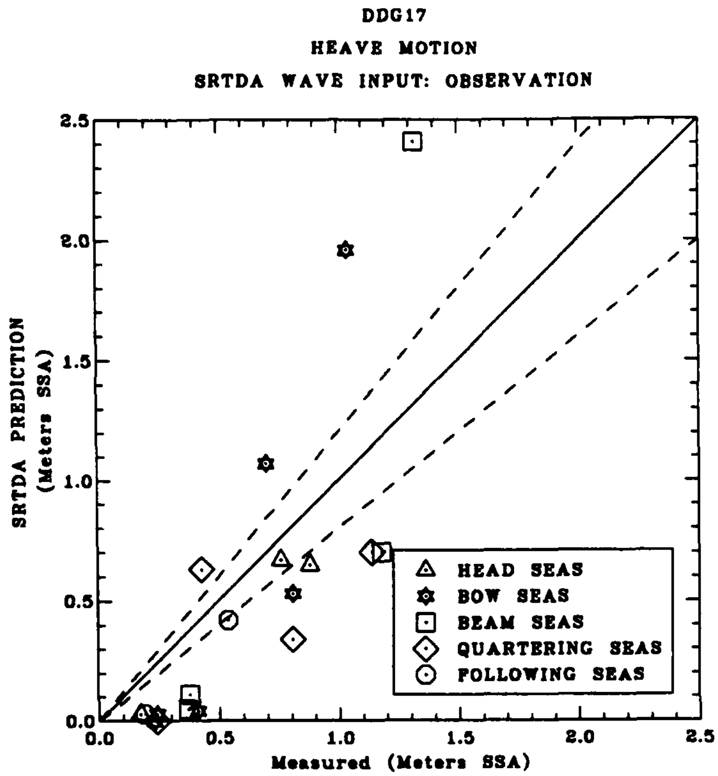


Figure 14. Predicted vs. Measured Heave Motions Grouped by Heading. Predicted Motions Based on Observed Waves.

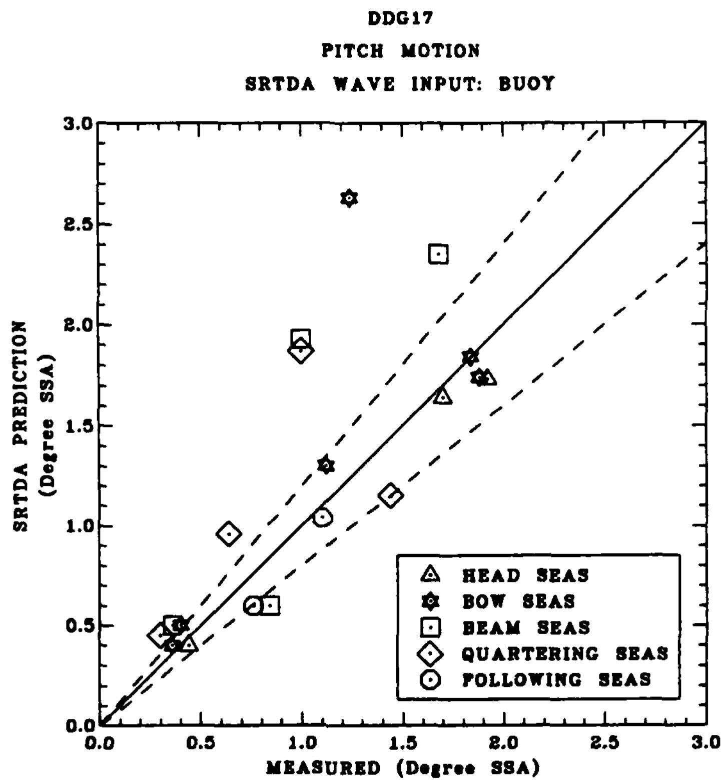


Figure 15. Predicted vs. Measured Pitch Motions Grouped by Heading. Predicted Motions Based on Buoy Measured Waves.

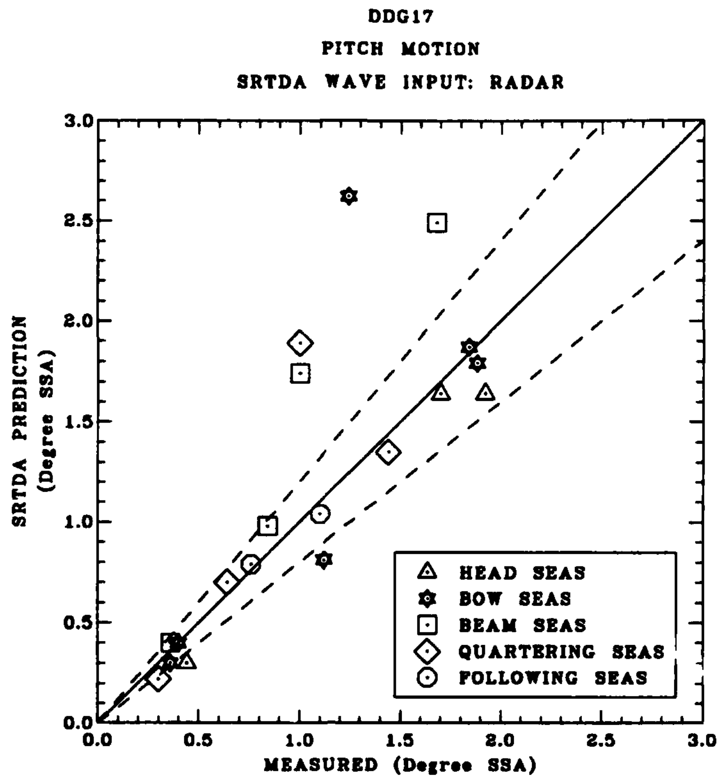


Figure 16. Predicted vs. Measured Pitch Motions Grouped by Heading. Predicted Motions Based on Radar Measured Waves.

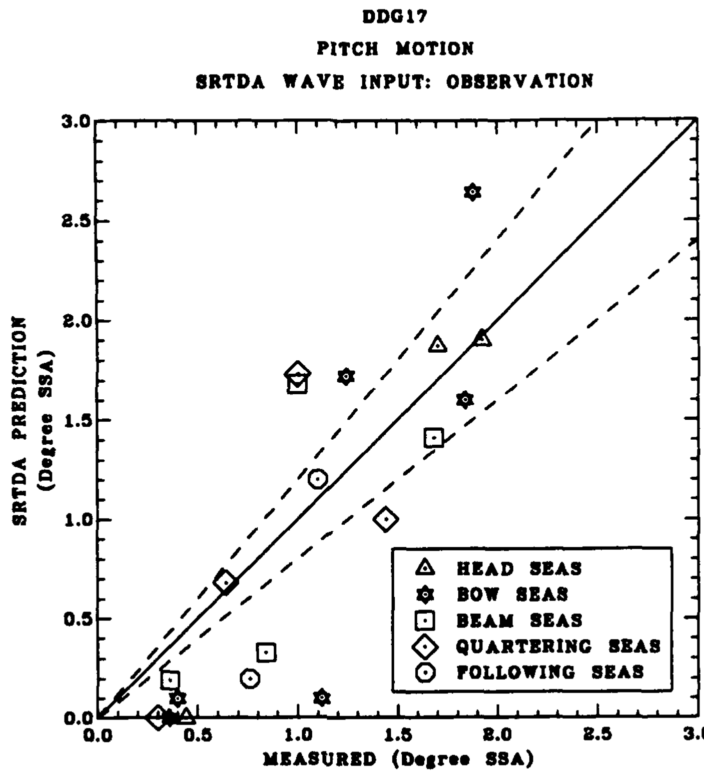


Figure 17. Predicted vs. Measured Pitch Motions Grouped by Heading. Predicted Motions Based on Observed Waves.

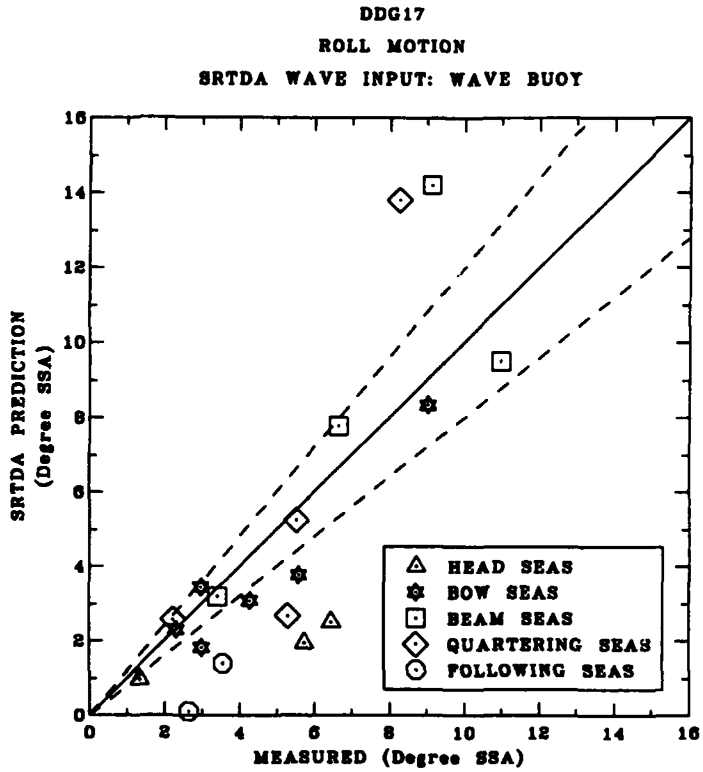


Figure 18. Predicted vs. Measured Roll Motions Grouped by Heading. Predicted Motions Based on Buoy Measured Waves.

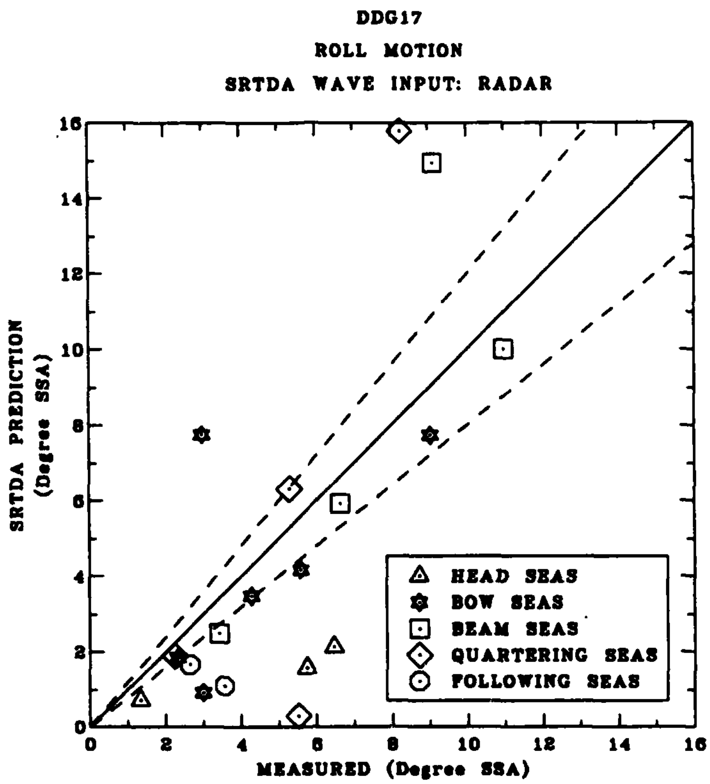


Figure 19. Predicted vs. Measured Roll Motions Grouped by Heading. Predicted Motions Based on Radar Measured Waves.

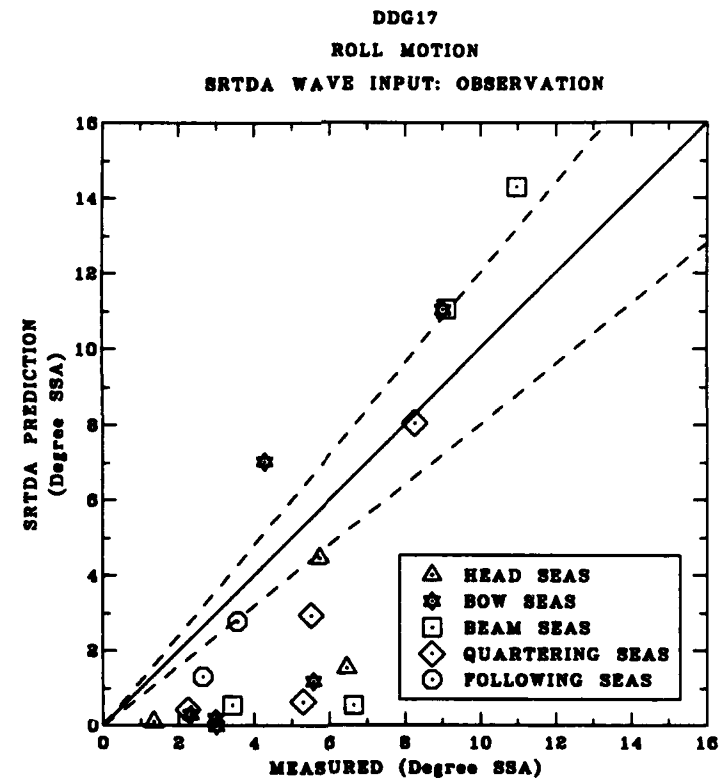


Figure 20. Predicted vs. Measured Roll Motions Grouped by Heading. Predicted Motions Based on Observed Measured Waves.

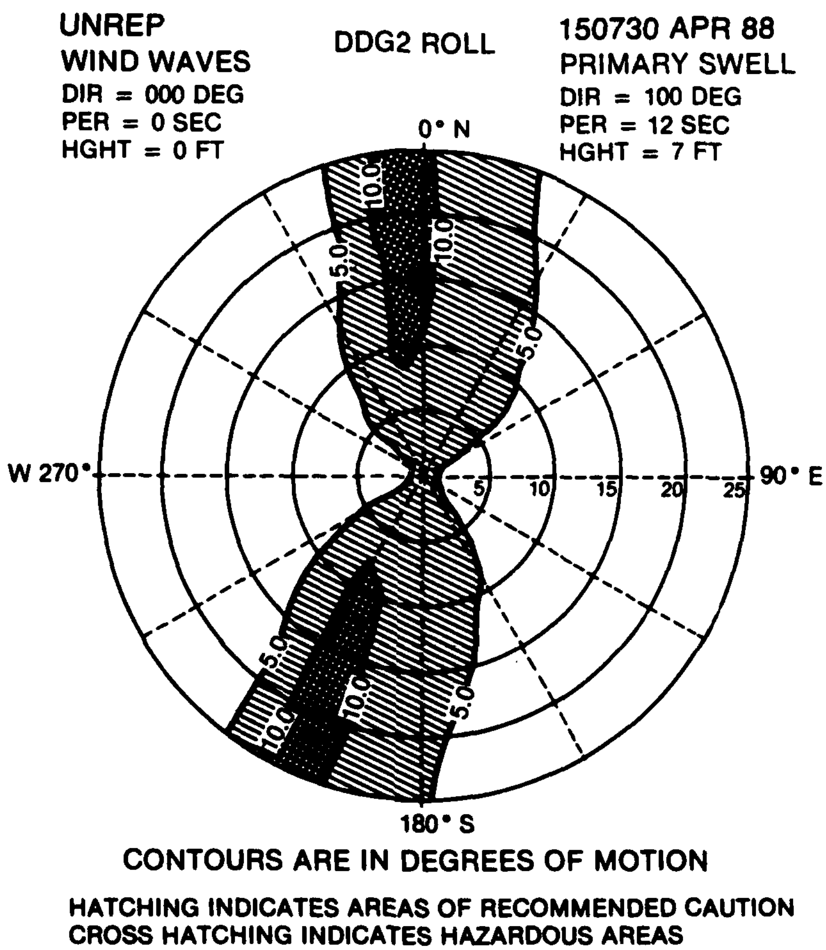


Figure 21. Speed Polar Plot of Levels of Operability of UNREP Due to Roll Motion.

Table 1. PSRM File Hull Numbers for Surface Ships in a Battle Group.

SHIP	PSRM No.	SHIP	PSRM No.
Aircraft Carriers			
CV41	141	CVN65	165
CV43	143	CV67	167
CV59-CV60	159	CVN68-70	168
CV61-CV62	161	CVN71	171
CV63-CV66	166		
Destroyers and Battleships			
DD931-DD951	946	BB61-BB64	201
DD963-DD997	963		
DDG2-DDG24	902		
DDG31-DDG34	931		
DDG37-DDG46	937		
DDG993-DDG996	993		
Frigates			
FF1037-FF1038	737	FFG1-FFG6	701
FF1040-FF1051	740	FFG7-FFG61	707
FF1052-FF1097	752		
FF1098	798		
Cruisers			
CG16-CG24	316	CGN36-CGN37	336
CG26-CG34	326	CGN38-CGN41	338
CGN9	309	CG47-CG68	347
CGN25	325		
CGN35	335		
Mine Warfare Ships			
MCM1-MCM8	801		

Table 1. (Continued)

SHIP	PSRM No.	SHIP	PSRM No.
Amphibious Warfare			
AGF11	605		
LPD1-LPD2	601		
LPD4-LPD15	604		
LHA1-LHA5	611		
LHD1-LHD3	621		
LPH2-LPH12	602		
LCC19-LCC20	619		
LKA113-LKA117	613		
Landing Craft Carriers			
LSD28-LSD35	628		
LSD36-LSD40	636		
LSD41-LSD46	641		
LST1179-LST1198	679		
Replenishment Ships			
	Full Load		Half Load
AE21-AE22	021		
AE23-AE25	023		
AE26-AE35	026		
AOE1-AOE4	001		501
AOR1-AOR7	010		510
AO177-AO187	077		577
AFS1-AFS7	011		
Miscellaneous Ships			
WHEC715	915		
WMEC901	901		
WMEC615	905		
TARC3	903		
TAGOS1-TAGOS16	911		

Table 2. Wave Measurements used as Input to the Ship Response TDA

	SEAS			SWELL		
MEASUREMENT TYPE	$H_{1/3}$ (m)	T_o (sec)	DIR (°T)	$H_{1/3}$ (m)	T_o (sec)	DIR (°T)
Octagon 1						
Buoy	0.98	10.6	056	—	—	—
Radar	†	9.8	047	—	—	—
Observation	0.91 (3 ft)	4.0	020	0.91 (3 ft)	5.0	050
Octagon 2						
Buoy	—	—	—	3.35	11.6	070
Radar	—	—	—	†	11.75	067
Observation	0.91 (3 ft)	10.0	030	3.05 (10 ft)	12.0	050
Octagon 3						
Buoy	—	—	—	3.35	11.6	079
Radar	—	—	—	†	12.1	082
Observation	—	—	—	2.43 (8 ft)	12.0	060
Octagon 4						
Buoy	—	—	—	2.04	11.6	101
Radar	—	—	—	†	11.9	145
Observation	0.61 (2 ft)	4.0	205	1.52 (5 ft)	8.0	065

† Buoy Measurement was used for TDA input.

Table 3. Percentage of Motion Predictions Within ±20%, Between ±20% and ±40%, and Greater than ±40% of the Measured Motion Levels based on Type of Wave Measurement and Motion.

MOTION	P≤ ±20%	$\pm 20 < P \leq \pm 40\%$	P> ±40%	No. of Samples
Buoy Measured Waves				
Heave	47	42	11	19
Pitch	47	26	26	19
Roll	42	21	37	19
Average	46	30	25	—
Radar Measured Waves				
Heave	42	32	26	19
Pitch	63	16	21	19
Roll	37	16	47	19
Average	47	21	32	—
Observed Waves				
Heave	5	26	68	19
Pitch	32	16	53	19
Roll	5	26	68	19
Average	14	23	63	—

Table 4. Percentage of Motion Predictions Within ±20%, Between ±20% and ±40%, and Greater than ±40% of the Measured Motion levels based on Octagon and Type of Wave Measurement.

TYPE OF MEASUREMENT	$P \leq \pm 20\%$	$\pm 20 < P \leq \pm 40\%$	$P > \pm 40\%$	No. of Samples
Octagon 1				
Buoy	60	33	7	15
Radar	47	33	20	15
Observation	0	0	100	15
Average	36	22	42	—
Octagon 2				
Buoy	40	33	27	15
Radar	47	13	40	15
Observation	33	33	33	15
Average	40	27	33	—
Octagon 3				
Buoy	33	27	40	15
Radar	53	20	27	15
Observation	13	53	33	15
Average	33	33	33	—
Octagon 4				
Buoy	50	25	25	12
Radar	42	17	42	12
Observation	8	0	92	12
Average	33	14	53	—

Table 5. Percentage of Motion Predictions Within ±20%, Between ±20% and ±40%, and Greater than ±40% of the Measured Motion Levels based on Motion and Type of Wave Measurement.

TYPE OF MEASUREMENT	$P \leq \pm 20\%$	$\pm 20 < P \leq \pm 40\%$	$P > \pm 40\%$	No. of Samples
Heave				
Buoy	47	42	11	19
Radar	42	32	26	19
Observation	5	26	68	19
Average	32	33	35	—
Pitch				
Buoy	47	26	26	19
Radar	63	16	21	19
Observation	32	16	53	19
Average	47	19	33	—
Roll				
Buoy	42	21	37	19
Radar	37	16	47	19
Observation	5	26	68	19
Average	28	21	51	—

Table 6. Percentage of Motion Predictions Within ±20%, Between ±20% and ±40%, and Greater than ±40% of the Measured Motion Levels based on Type of Wave Measurement and Heading.

HEADING	$P \leq \pm 20\%$	$\pm 20 < P \leq \pm 40\%$	$P > \pm 40\%$	No. of Samples
Buoy Measured Waves				
Head Seas	55	33	11	9
Bow Seas	50	44	6	18
Beam Seas	42	33	25	12
Quartering Seas	50	0	50	12
Following Seas	33	33	33	6
Average	46	30	25	—
Radar Measured Waves				
Head Seas	33	33	33	9
Bow Seas	61	17	22	18
Beam Seas	50	17	33	12
Quartering Seas	42	17	42	12
Following Seas	33	33	33	6
Average	47	21	32	—
Observed Waves				
Head Seas	33	22	44	9
Bow Seas	6	22	72	18
Beam Seas	8	25	67	12
Quartering Seas	17	17	67	12
Following Seas	17	33	50	6
Average	14	23	63	—

Table 7. The Mean and Standard Deviation of the Differences between Predicted and Measured Motion, Based on Type of Wave Measurement and Type of Motion.

- **Percent Differences between Predicted and Measured Motion**

	MOTION					
	HEAVE		PITCH		ROLL	
TYPE OF MEASUREMENT	MEAN	STD DEV	MEAN	STD DEV	MEAN	STD DEV
Buoy	8.5	63.7	22.0	40.2	-17.1	40.2
Radar	-0.1	60.5	12.0	39.0	-13.7	60.4
Observation	-35.0	59.6	-24.4	55.6	-46.2	50.1

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